

METHODS TO INCREASE ELECTRICAL BREAKDOWN THRESHOLD OF POLYSTYRENE INSULATORS

Jennifer L. Zirnheld⁺, Kevin M. Burke⁺, Shola Olabisi⁺, Jahmil Campbell⁺, Harry Moore⁺⁺,
Dave Singh⁺⁺

⁺*Energy Systems Institute, University at Buffalo, The State University of New York
312 Bonner Hall, Buffalo, NY 14260*

⁺⁺*U.S. Army RDECOM-ARDEC Advanced Energy Armament Systems Center
Bldg. 65N, Picatinny Arsenal New Jersey 07806, USA*

Abstract

This paper discusses experimental studies conducted to determine the effects of methods used to increase the electrical stress limit of polystyrene dielectric samples. Surfaces of samples were laser annealed to create a more uniform surface and decrease voids where charge may accumulate. Geometry of the dielectric samples were considered with the aim of reducing electric field intensity at the triple point formed by the cathode, dielectric, and ambient environment, which in the presence of a strong electric field can become a source for electron emission. The dielectric samples were subjected to high voltage stress via a custom built partial discharge analyzer (PDA) capable of delivering 40 kVac, 20 kVdc or ac superimposed on dc. Preliminary results have shown that annealing of the surface has increased the hold-off voltage of the dielectric samples in comparison to benchmark samples that were not annealed. Studies have shown that reduction of the electric field intensity at the triple point can increase the voltage at which secondary electron emission avalanche initiates, which is widely agreed upon as the process preceding the onset of surface flashover. Experimental results are discussed and related to factors of interest including electric field intensity at the triple point, flashover hold off voltage and correlation with methods applied.

I. INTRODUCTION

Utilization of dielectric materials for the impediment of current flow and voltage build-up has become an integral part in electrical systems used for pulsed power applications that require high voltage and short rise times. Electrical breakdown of these insulators is an important consideration when designing such systems and circuitry. Dielectric material should be selected based on a number of material characteristics and desired performance specifications. Aging due to high voltage stress and partial discharge (PD) phenomena are critical characteristics to take into consideration when

determining the lifetime of dielectric materials used within high voltage systems.

Partial discharges are a localized partial dielectric breakdown of a solid or liquid insulator under high voltage stress. Discharges partially bridge the gap between electrodes; hence it is denoted as a partial discharge into the dielectric [1]. Partial discharges can be initiated due to voids, cracks, and inclusions within a solid dielectric and often originates from the interface between the conductor and dielectric and can be attributed to aging and long term failure in dielectric materials [1]. Repeated exposure to partial discharge can lead to electrical breakdown of the insulator, which is a rapid reduction of the resistance of the insulator. This leads to a conductive path that can lead to electrical sparks and/or discharge through the bulk of the insulator or across the surface of the insulator. Surface breakdown is the form of breakdown most commonly seen in applications where high voltage is applied to dielectric insulators.

Results in [2] have shown that flashover on or near the surface of the dielectric can occur at a voltage considerably lower than the voltage necessary for bulk breakdown or breakdown of the vacuum gap in the absence of the dielectric. This discharge oftentimes manifests itself as a corona discharge with the capacity to damage surrounding circuitry as it flashes from the surface of the dielectric to ground. The capacity for damage to the system is determined by severity of the breakdown and whether there is a clear discharge path.

It is important to reduce the occurrence of partial discharge events, as partial discharges through the bulk of the dielectric can have the effect of changing the chemical characteristics of the material, leading to degradation and eventual breakdown. A single partial discharge erodes $1 \cdot 10^{-15} \text{ cm}^3$ of solid material, and can also form gases that cause further degradation of the dielectric material at a rate of $1 \cdot 10^{-3} \text{ cm}^3$ per discharge [3].

The ability of dielectrics to sustain high voltages is usually limited by flashover on the surface of the dielectric [4-5], thus increasing the dielectric's ability to hold off flashover will significantly increase the lifetime of the dielectric [6].

Report Documentation Page		Form Approved OMB No. 0704-0188
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.		
1. REPORT DATE JUN 2009	2. REPORT TYPE N/A	3. DATES COVERED -
4. TITLE AND SUBTITLE Methods To Increase Electrical Breakdown Threshold Of Polystyrene Insulators		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER	
	5e. TASK NUMBER	
	5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army RDECOM-ARDEC Advanced Energy Armament Systems Center Bldg. 65N, Picatinny Arsenal New Jersey 07806, USA		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited		
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.		
14. ABSTRACT This paper discusses experimental studies conducted to determine the effects of methods used to increase the electrical stress limit of polystyrene dielectric samples. Surfaces of samples were laser annealed to create a more uniform surface and decrease voids where charge may accumulate. Geometry of the dielectric samples were considered with the aim of reducing electric field intensity at the triple point formed by the cathode, dielectric, and ambient environment, which in the presence of a strong electric field can become a source for electron emission. The dielectric samples were subjected to high voltage stress via a custom built partial discharge analyzer (PDA) capable of delivering 40 kVac, 20 kVdc or ac superimposed on dc. Preliminary results have shown that annealing of the surface has increased the hold-off voltage of the dielectric samples in comparison to benchmark samples that were not annealed. Studies have shown that reduction of the electric field intensity at the triple point can increase the voltage at which secondary electron emission avalanche initiates, which is widely agreed upon as the process preceding the onset of surface flashover. Experimental results are discussed and related to factors of interest including electric field intensity at the triple point, flashover hold off voltage and correlation with methods applied.		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

II. BACKGROUND

A. Secondary Electron Emission Avalanche

Flashover is believed to occur in three phases: initiation, propagation, and discharge. Initiation involves the freeing of electrons from the cathode-dielectric-ambient environment junction (triple point) due to the presence of a strong electric field. These electrons are freed generally by field emission or thermal-field emission. The removal of electrons results in an accumulation of positive charge which draws emitted electrons back to the surface. Emitted electrons that are drawn back to the surface then impact the surface and free other (secondary) electrons; this is known as the emitted electron's secondary electron emission (SEE) yield. As the positive charge grows at the cathode so too does the rate of field emitted electrons, resulting in the formation of a space charge above the surface [2].

B. Geometry

The importance of reducing the electric field at the triple point as a means of impeding the onset of flashover must be considered as a method to increase the breakdown threshold of the dielectric samples. One of the most effective ways to reduce the field at the triple point is to alter the angle of interface between the dielectric and cathode at the triple point [8-9]. Studies conducted in [9] have shown a direct correlation between shape of the insulator and surface flashover. Changing the angle of the dielectric at the triple point impacts flashover by modifying the local electric field and also changing the conditions by which electrons propagate along the surface of the dielectric [8]. Reducing the electric field at the triple point will hinder the facilitation of the initiation phase making it harder for electrons to be liberated from the cathode thus decreasing the dielectric's susceptibility to flashover.

III. METHOD

Experiments were conducted to determine the effectiveness of methods to suppress dielectric breakdown and resultant flashover. Two methods were employed to gauge their impact on breakdown voltage of dielectric samples. Sample geometry was chosen, with the aim of modifying the local electric field intensity at the cathode, dielectric, ambient environment triple point in order to increase flashover thresholds. Surface treatment of samples was also considered to increase the breakdown threshold of dielectric samples. Samples were treated on one surface with an excimer laser to remove defects and voids from the surface, in which excess charge from

SEEA could accumulate and build up until surface discharge occurs.

A. Laser Annealing / Surface Conditioning

Samples were subjected to excimer laser processing (XLP) in which one surface was ablated with an excimer laser to reduce electron traps and create a more uniform grain size on the treated surface [6]. This surface conditioning method allows for the removal and/or recrystallization of thin surface layers of the dielectric without thermal or chemical effects on the bulk, depending on the pulse width of the laser and optical absorption coefficient of the dielectric material [11].

XLP provided for the rapid melting and recrystallization of the surface skin layer. Radiation from the excimer laser is typically absorbed in a shallow depth range of around, 50-200 nm. This is favorable as ultraviolet (UV) radiation is readily absorbed by most materials, and UV wavelength is within that range of absorption. The shallow region of absorption, coupled with short pulse durations provides an ideal surface conditioning method [11].

B. Dielectric Samples

Initial investigations into the effectiveness of laser annealing as a viable method to impede the onset of flashover were conducted utilizing two different dielectric materials: polymethyl methacrylate (PMMA) and polystyrene (PS). Experiments conducted have shown that laser annealing has had a much greater effect on polystyrene (PS) samples in comparison to polymethyl methacrylate (PMMA) samples, with respect to recrystallizing the surface in an effort to remove inherent surface defects, voids and cracks [6]. Samples were processed at AMBP Tech Corporation. AMBP Tech Corporation utilized its expertise with laser annealing and vacuum technologies to modify the microscale structures on the surface of the polymer insulators in an effort to increase the electrical strength of these insulators. Samples were cut into right cylindrical geometries with a diameter of 5.10 cm and thickness of .624 cm.

Insulator samples were annealed at different energy densities and number of laser pulses per unit area was varied. Insulator samples were also annealed employing various contact angles between the laser and the insulator surface in different ambient gasses [6].

Observation of the surface showed that the PMMA samples were smoother than the surface of the PS samples. The PS samples responded much more favorably to the annealing process, showing a reduction in grain size and smoother surface. The following figures show images taken with a scanning electron microscope (SEM) of un-annealed samples, compared to annealed samples to show the affects of the surface conditioning. Comparing the PMMA samples to the PS samples, the un-annealed (benchmark) PMMA samples have a much smoother

surface in comparison to the surface of benchmark PS samples that show a defined, unordered grain structure. Post annealing the PMMA sample annealed at 500 mJ/cm^2 shows little difference in comparison to the un-annealed sample, while figure 1 (c) shows that the surface was actually damaged by the annealing process.

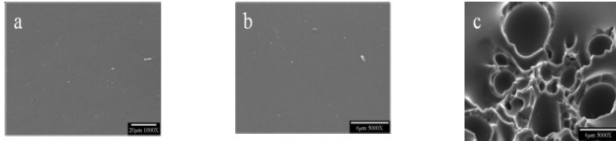


Figure 1. (a) PMMA un-annealed, (b) PMMA annealed at 500 mJ/cm^2 in nitrogen, (c) PMMA annealed at 1000 mJ/cm^2 in nitrogen

The PS samples annealed at 500 mJ/cm^2 both show a much smaller grain, and more orderly surface in comparison to the un-annealed sample in figure 2 (a).

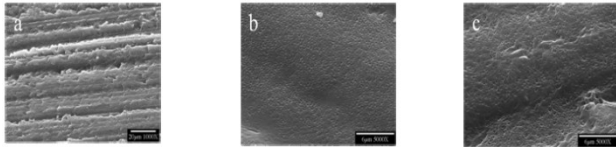


Figure 2. (a) PS un-annealed, (b) PS annealed at 500 mJ/cm^2 in nitrogen, (c) PS annealed at 500 mJ/cm^2 in sulfur hexafluoride

The study conducted in [6] found a correlation between the surface conditioning by laser annealing, and an increase in the amount of voltage the samples would withstand before flashover. The PS samples outperformed the PMMA samples in terms of breakdown voltage, and were not prone to surface damage from the annealing process at higher energy densities.

For this study we are focusing solely on PS insulators and increasing the voltage thresholds beyond previous results.

IV. EXPERIMENTAL SETUP

Of interest is the dc voltage at which breakdown occurs, as dc voltage will simulate worst case scenario for employment of the dielectric. 10 of the samples included in this study were annealed at a fluence of 9.4 mJ/cm^2 , and held at a fixed wavelength rather than a fixed angle. In comparison to fixing the angle of contact between the laser and the surface, in which the depth of penetration into the surface of the insulator r from 50-200 nm, fixing the wavelength may provide a much more uniform grain structure on the surface of the insulator. Post annealing, the PS samples were subjected to high voltage stress via a custom built partial discharge analyzer (PDA). The PDA is capable of delivering 40 kV ac, 20 kV dc, or ac superimposed on dc. Figure 3 shows the test stand that was constructed and allows for the application of the high

voltage via an electrode (Anode) pressed onto the surface of the dielectric sample. The sample rests on a copper ground plane (cathode).

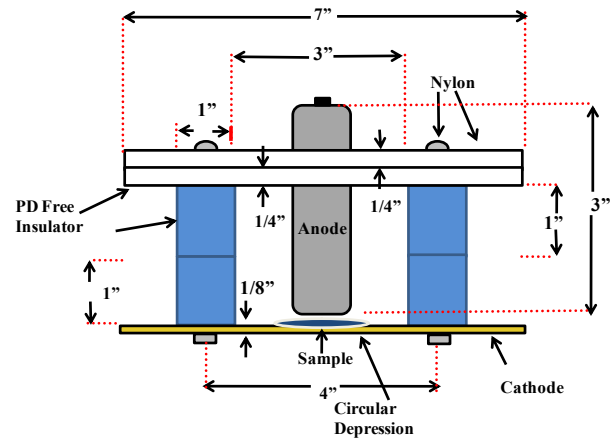


Figure 3 Test Fixture

The test setup shown in Figure 3 was placed in a vacuum chamber and evacuated to a pressure of 48.8 torr (1.92 in Hg). High voltage feed-throughs connect the stainless-steel anode and copper ground plane of Figure 3 to high voltage and ground on the PDA. The unequal diameter electrode arrangement utilized for testing complies with the recommendations in publication 243 of the International Electro-technical Commission Specification (IEC) and ASTM D 149.

It was postulated that interfacing the annealed side with the cathode, in conjunction with the cylindrical geometry may show improved results over those previously observed. Taking cathode initiated breakdown at the cathode, insulator, ambient environment junction as the mechanism that allows for the field emission of electrons. Reducing the electric field at the triple point, and interfacing the cathode with the annealed surface of the insulator, it is believed that the insulator will breakdown at higher voltages that previously observed. All samples were tested in two orientations; Annealed side facing the anode (AFA), and annealed side facing the cathode (AFC). Results were obtained and analyzed. 30 samples (5 samples per energy level) were selected and cleaned with distilled water for 30 minutes in an ultrasonic cleaner. The samples were then allowed to dry for 72 hours in a dehumidifier. All 30 samples were then tested with the annealed side facing anode. The samples were then re-cleaned and allowed to dry in the dehumidifier for 72 hours, before being tested with the annealed side facing the cathode. Results were compiled and average values were compared. Results were plotted against benchmark values as well as against themselves with respect to orientation.

Table 1. List of samples tested

Material	Laser Fluence (mJ/cm ²)	Annealing Angle (°)	Wavelength (nm)
PS	0	90	N/A
PS	250, 500, 750, 1000	45	N/A
PS	9.4	N/A	157
PS	9.4	N/A	193

V. RESULTS

Results were separated into two groups based on the orientation of the samples (AFA or AFC) when tested. The results were then plotted against the un-annealed PS samples denoted as benchmark samples, and also plotted against each other separated by orientation. Observations from initial results show that the samples tested AFC performed better than those tested AFA, and that the samples annealed at a fixed wavelength performed comparatively to samples annealed at much higher laser fluence energy densities.

A. Annealed Side Facing Anode

DC results obtained are shown in Figure 4. 30 samples (5 samples from each laser fluence energy density) were tested with the annealed side facing anode. DC arcing values obtained were compared to benchmark values obtained from un-annealed PS samples. Results displayed in Figure 4 show samples annealed at a laser fluence of 9.4 (mJ/cm²) and a wavelength of 193 nm arcing at an average value of 6.33 V which is a 22% increase over the benchmark value of 5.18 V.

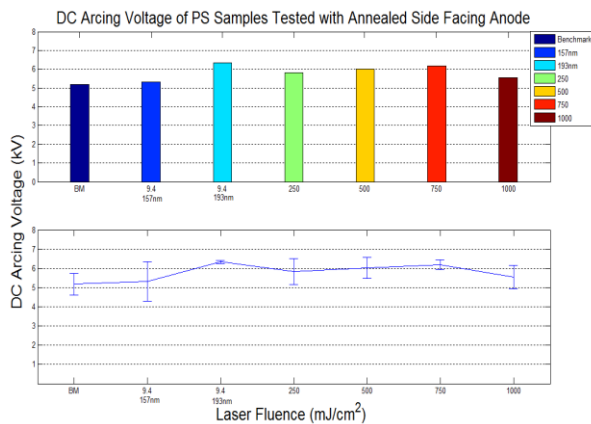


Figure 4. DC results of PS samples tested with annealed side facing anode

This average DC arcing value is consistent with results obtained from previous tests which yielded an average DC arcing value of 6.39 V, the second highest average DC arcing value of the previous group.

B. Annealed Side Facing Cathode

DC results obtained are shown in Figure 5. 30 samples (5 samples from each laser fluence energy density) were tested with the annealed side facing cathode. DC arcing values obtained were compared to benchmark values obtained from un-annealed PS samples. Results displayed in Figure 5 show samples annealed at laser fluence of 1000 (mJ/cm²) arcing at an average voltage of 6.87 V which is a 33% increase over the benchmark average arcing value. The trend among these samples showed increasing arcing voltages as the laser fluence increased.

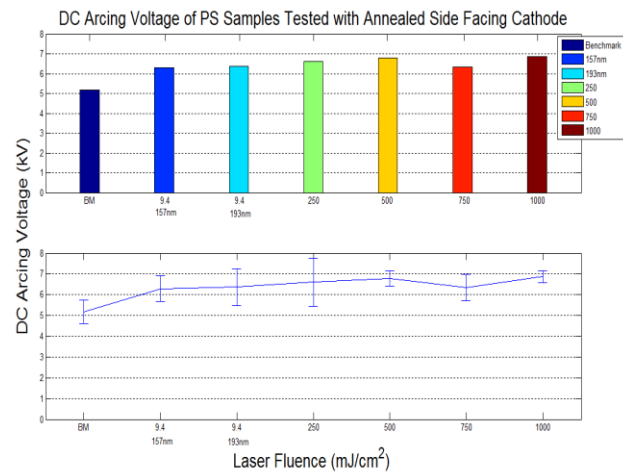


Figure 5. DC results of PS samples tested with annealed side facing cathode

C. AFA vs. AFC

Results of DC arcing values obtained for samples tested with annealed side facing anode are compared to arcing values of samples tested with annealed side facing cathode and displayed in Figure 6. The samples tested with annealed side facing the cathode had higher average arcing voltages in comparison to samples tested with the annealed side facing the anode. The largest difference was observed by samples annealed at a laser fluence of 1000 (mJ/cm²). Samples in the 1000 (mJ/cm²) group tested in AFC orientation had an average arcing voltage of 6.87 V which was a 24.03% increase over average arcing value of the samples tested in AFA orientation, which had an average arcing voltage of 5.54 V. The percent increase in average arcing values of AFC over AFA is displayed as above the average arcing values for the AFC samples in

Figure 6 below. The smallest percent increase was observed at the laser fluence of 9.4 (mJ/cm²) and a wavelength of 193 nm at a value of 0.69%.

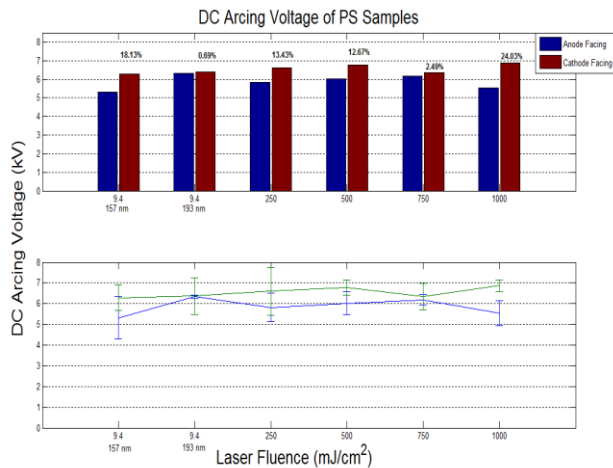


Figure 6. DC results of PS samples tested AFA Vs AFC

IV. SUMMARY AND CONCLUSION

Results obtained from the experiments conducted give credence to the theory of cathode initiated breakdown as the mechanism that precedes flashover and initiates SEEA, as the samples tested in AFC orientation all had higher average arcing values than when tested in the AFA orientation. As the laser fluence increased the difference in average arcing values became more pronounced for the most part. This may be attributed to orienting the sample with the annealed side facing the cathode, which helped to impede cathode initiated breakdown. Results have shown that the samples arced at higher DC voltages when tested in AFC orientation in comparison to when tested in AFA orientation. Average arcing values for AFC were all above 6 kV but did not reach above 7 kV.

Comparing results of the samples annealed at a fixed wavelength to samples annealed at a fixed angle of contact between the laser and the surface, samples annealed at a fixed angle of contact showed higher average arcing values when compared to values of the fixed wavelength samples. Average arcing values for the samples annealed at a fixed wavelength were surprisingly close to samples annealed at a fixed angle, as the laser fluence of the samples annealed at fixed wavelength were significantly lower than the comparative samples. This warrants further investigation into the benefits of controlling the wavelength of the laser during the annealing process as a means to achieve a smaller more oriented grain size on the surface and reduce the number of surface defects.

V. ACKNOWLEDGMENT

Original effort sponsored by AMBP Tech Corporation through a grant from the US Army ARDEC/Picatinny Arsenal. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the AMBP Tech Corporation.

VI. REFERENCES

- [1] Bodega, R.; Morshuis, P.H.F.; Lazzaroni, M.; Wester, F.J., "PD recurrence in cavities at different energizing methods," *Instrumentation and Measurement, IEEE Transactions on*, vol.53, no.2, pp. 251-258, April 2004
- [2] R. A. Anderson "Mechanism of fast surface flashover in vacuum", *Appl. Phys. Lett.*, Vol. 24, pp. 54-56, 1974
- [3] R. Bartinkas, *Engineering Dielectrics* vol. IIB. Philadelphia: Special Technical Publications 926, 1987
- [4] P. H. Gleichuf, "Electrical Breakdown over Insulators in High Vacuum", *J. of Appl. Phys.*, Vol. 22, pp. 766, 1951
- [5] R. A. Anderson, "Surface Flashover: Three Decades of Controversy", *XIVth International Symposium on Discharges and Electrical Insulation in Vacuum*, pp. 286, 1990
- [6] J. Zirnheld, S. Olabisi, P. Strzempka, K. Burke, Y. S. Ali, A. Belkind, and G. Tompa, "Laser Annealing Effects on DC Surface Flashover of PMMA and Polystyrene," in *IEEE International Power Modulators and High Voltage Conference, Proceedings of the 2008*, 2008, pp. 276-279.
- [7] K. D. Bergeron "Theory of the secondary electron avalanche at electrically stressed insulator-vacuum interfaces", *Journal of Applied Physics*, Vol. 48, pp. 3073-3080, 1977
- [8] H. C. Miller "Surface Flashover of Insulators", *IEEE Transactions EI*, Vol. 24, pp. 765-786, 1989
- [9] J. M. Wetzler, P. A. A. F. Wouters "The Effect of Insulator Charging on Breakdown and Conditioning", *IEEE Transactions EI*, Vol. 28, pp. 681-691, 1993
- [10] V. A. Nevrovsky, "Analysis of elementary processes leading to surface flashover in vacuum," in *Discharges and Electrical Insulation in Vacuum, 1998. Proceedings ISDEIV. XVIIIth International Symposium on*, 1998, pp. 159-161 vol.1.

[11]M. Hood “Effect of Laser Annealing on Partial Discharge Behavior in Alumina Dielectrics”, Master’s thesis, department of electrical engineering, State University of New York at Buffalo, Buffalo, New York, USA, 2007.

[12]A. Emelyanov, E. Emelyanova, T. Safonova, and I. Serikov, "Estimation of cathode-initiated breakdown in vacuum," *Dielectrics and Electrical Insulation*, IEEE Transactions on, vol. 13, pp. 26-33, 2006.